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Smoothed particle hydrodynamics numerical model for modeling an oscillating water chamber

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ABSTRACT

This paper presents the application and the validation of the SPH numerical model SPHyCE, based on a standard Smoothed Particle Hydrodynamics formulation, for modeling an onshore oscillating water chamber, comparing results of amplification factor and phase lag with those obtained by a mesh-based RANS model. Firstly, an analysis of the results for different resolutions (i.e. particle dimension) showed the independence of results with refinement. Secondly, the amplification factor of mean free surface elevation inside the oscillating water chamber and the phase lag between time series of free surface elevation outside and inside the water chamber were analysed. A good agreement was achieved between the mesh free SPHyCE model and the mesh-based RANS model. SPHyCE model was finally applied to analyse the hydrodynamic fluid flow inside and outside the water chamber and to quantify the forces on the vertical wall and the amplification factor for different incident wave heights for a rough sea state with complex wave breaking, impact loads and overtopping, contributing to the future applications of SPH models for development and studies of OWC devices.

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1. Introduction

Numerical models based on the Lagrangian formulation of Navier-Stokes equations, such as the Smoothed Particle Hydrodynamics (SPH) approach, have emerged for modeling complex free surface flows (Monaghan, 1994). The method is based on a completely mesh-free technique which allows modeling fluid particle trajectories. Different codes have been developed, based on the incompressible SPH (ISPH) and the weakly-compressible SPH (WCSPH) formulation of the Navier-Stokes equations, and there are many different numerical implementations.

The SPHyCE numerical model, developed and used at the National Laboratory for Civil Engineering (LNEC), was based on the original SPHysics model (SPHyscis code v1.4, 2009; Gómez-Gesteira et al., 2010, 2012) and standard SPH approach of Monaghan (1994). It was specifically modified and improved for coastal engineering studies involving complex wave interactions with impermeable and porous structures. The numerical model includes specific developments for coastal engineering applications, namely: (i) a wave-maker with active absorption and with a paddle drift correction allowing the simulation of a semi-infinite numerical wave flume and obtaining long time series for statistical analyzing; (ii) and a coupling technique between SPHyCE model, which allows modeling complex wave-coastal structures interaction, and a less CPU demanding numerical model appropriate for wave propagation, such as Reynolds-Average Navier-Stokes (RANS) or Eulerian model. With these specific implementations, promising agreement with experimental data has been obtained for the wave propagation, wave breaking, overtopping and impact loads in vertical and porous coastal structures (Didier and Neves, 2012; Didier et al., 2012, 2013, 2014, 2014b, 2015).

This study is focused on the first application of SPHyCE model for wave energy converters, mainly for oscillating water column (OWC) devices, a current international interest of investigation and development. The main goal is to verify the applicability of the SPHyCE for studies of OWCs interacting with rough wave conditions, with wave breaking and strong impact loads on the structure, conditions for what SPH models are more appropriated than RANS-VoF (Volume of Fluid) models.

The model is presented and applied for a simple wave flume (horizontal bottom) with an oscillating water chamber at the end. This simple geometry was defined to study the effectiveness of the SPHyCE model, without the complex dynamics of the wave breaking or overtopping phenomenon, i.e. for analyzing its

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capabilities to model the complex nonlinear interactions between the incident waves and a simple OWC structure.

Firstly, an analysis of the influence of different resolutions, i.e. particle dimension, on the results was performed for defining the better compromise between the independence of the results on the particle dimension and the CPU time, for an incident wave height of 2.0 m and a wave period of 7 s. Secondly, SPHyCE model was applied to study the resonance into the oscillating water chamber, considering an incident wave height of 2.0 m and a range of wave periods from 4 to 12 s. Results of mean wave heights inside the water chamber and phase lag between the wave inside and outside the chamber were compared with the FLUENT mesh-based code. This model had already been successfully applied to this type of studies, more specifically for oscillating water column devices for wave energy production (el Marjani et al., 2008; Paixão Conde and Gato, 2008; Paixão Conde et al., 2011; Didier et al., 2011; Zhang et al., 2012; Teixeira et al., 2013). Based on these results, the accuracy with the resolution used in SPH simulations is confirmed. Finally, SPHyCE model was applied for an incident wave with a wave height varying from 1.0 to 6.0 m and a wave period of 9 s with the objective of assessing the capabilities of the numerical model and analyzing wave-structure interaction for a rough sea state with complex wave breaking, impact loads on vertical wall of oscillating water column device and overtopping.

SPH models are better adapted for simulating this type of very complex wave-structure interactions when comparing to RANS-VoF models and can be used in future studies of oscillating water column devices with complex geometries and with all type of incident wave conditions. The present applications show that SPH model allows predicting accurately the performance of OWC devices and the forces on their structures by using a small numerical domain, a long data capture and a rough sea state.

2. SPHyCE numerical model

The Smoothed Particle Hydrodynamics (SPH) numerical methods were initially applied to astrophysics by Gingold and Monaghan (1977) and Lucy (1977) and later to hydrodynamics by Monaghan (1992, 1994). The SPH method is a completely mesh-free technique, enabling the modeling of the fluid particle trajectories considering the Navier-Stokes equations written on the SPH formalism, based on the theory of interpolation integrals which use interpolation kernels.

The Lagrangian approach of the SPH methods allows following the fluid particles in a determined time interval in order to obtain their trajectories, velocities and pressures as a function of the initial position and time.

The two-dimensional Navier-Stokes equations in Lagrangian form for a viscous fluid, in a referential ($0xy$), are used and written as

$$\frac{d\boldsymbol{v}}{dt} = -\frac{1}{\rho}\nabla P + \boldsymbol{\Pi} + \boldsymbol{g} \tag{1}$$

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\,\mathrm{div}(\boldsymbol{v}) \tag{2}$$

where t refers to the time, $\boldsymbol{v}$ the velocity vector, P the pressure, ρ the fluid density, $\boldsymbol{\Pi}$ the viscous terms and $\boldsymbol{g}=(0, -9.81\ \mathrm{m/s^2})$ the gravitational acceleration.

The standard SPH formulation (Monaghan, 1994), in which the fluid is considered weakly-compressible, is used and the pressure is calculated by an equation of state (Batchelor, 1974) through the fluid density:

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{3}$$

where $\gamma = 7$, $B = c_0^2\rho_0/\gamma$, $\rho_o = 1000\ \mathrm{kg/m^3}$ is the reference density for water and c_o is the speed of sound at the reference density.

The particle trajectories are obtained from the following relationship:

$$\frac{d\boldsymbol{r}}{dt} = \boldsymbol{v} \tag{4}$$

where $\boldsymbol{r}$ is the particle position vector.

Equations are writing using the fundamental principle of the SPH methods which consists to approximate a scalar, a function or a tensor using the theory of the interpolation integrals. The integral of an interpolation function $f(\boldsymbol{r})$ over a volume V depend on the particle position $\boldsymbol{r}$, the kernel function, W, an analytic function which can be differentiated without requiring any spatial mesh and allows determining the interaction among neighboring particles included in the kernel influence domain, and the smoothing length h that allows to define the size of the kernel (Gómez-Gesteira et al., 2012). Numerically, the function $f(\boldsymbol{r})$ is written as an approximation of the function f at a particle a at the position $\boldsymbol{r}_a$.

$$f(\boldsymbol{r}_a) \approx \sum_b m_b \frac{f_b}{\rho_b} W_{ab} \tag{5}$$

where f_b is the value of the function f associated with the particle b at $\boldsymbol{r}_b$, $W_{ab} = W(\boldsymbol{r}_a - \boldsymbol{r}_b, h)$ is the value of the kernel at $(\boldsymbol{r}_a - \boldsymbol{r}_b)$. As in SPH the mass, m_b, of particle b remains fixed and the density, ρ_b, might fluctuate, the volume of the particle is replaced by m_b/ρ_b.

For numerical simulation of wave propagation, the quadratic kernel (Johnson et al., 1996; Dalrymple and Rogers, 2006) is used for determining the interaction between particles. Previous studies show that this kernel provides good results when compared with experimental data and other numerical results (Didier et al., 2012, 2013, 2014, 2015). The kernel is defined by the analytic function:

$$W(q, h) = \frac{3}{2\pi h^2}\left(\frac{q^2}{4} - q + 1\right) \tag{6}$$

where $q = r/h$ $(0 \le q \le 2)$ and r is the distance between particles a and b. This kernel has the particularity of not having an inflection point in its first and second derivatives in the range of the function definition.

The SPHyCE numerical model used and improved at LNEC is based on the open-source code SPHysics (Gómez-Gesteira et al., 2010, 2012; SPHysics code v1.4, 2009), inspired by the SPH standard formulation of Monaghan (1994). The fluid in the standard SPH formalism is treated as weakly-compressible, allowing the direct pressure calculation through the state equation (Batchelor, 1974), that relates the fluid pressure with the density.

The discrete momentum equation proposed by Monaghan (1992) was used to determine the acceleration of a particle a as the result of the particle interaction with the neighbor particle b.

The turbulence model Sub-Particle Scale (SPS) (Gotoh et al., 2001) is preferentially used since it includes not only a viscosity model but also the turbulence effect through a model derived from the LES-type models (Large Eddy Simulation). The artificial viscosity model (Monaghan, 1992), with two empirical parameters that should be calibrated, is frequently used to stabilize the numerical process but introduces a numerical diffusion that might affect significantly the wave amplitude (Didier and Neves, 2009).

The mass conservation equation in the discrete SPH formalism allows calculating changes in fluid density, since the mass of each particle is constant.

The fluid is treated, as referred before, as weakly compressible and the equation of state, Eq. (3), is used for calculating the fluid pressure.

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